# Toward A New Nuclear Regime

Jor-Shan Choi and Thomas H. Isaacs
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551-0808
E-mails: choi1@llnl.gov, isaacs2@llnl.gov

**Abstract -** *Many in the nuclear community are beginning to anticipate a return to significant growth of new nuclear power generation in the coming decades. The growth in global demand for energy, the increased recognition of the impacts of carbon dioxide emissions from fossil fuel plants, and a new generation of safe, economic plants are seen as fundamental drivers towards a nuclear resurgence. Others are less optimistic, but believe that, at a minimum, the option for countries to turn to nuclear power to meet growing energy demands should not be precluded. Still others believe that past peaceful nuclear activities have resulted in serious, unsolved problems associated with waste management and ultimate disposal, aggravated proliferation concerns, caused significant safety incidents, and resulted in a decrease in public acceptance in many countries. This has led to the proposed shutdown and abandonment of current nuclear power plants in several countries. If there is to be a resurgence of nuclear power generation, what are the technical, institutional, and societal issues that must be resolved? There is often an assumption that stopping nuclear power is the most effective way to minimize proliferation and stop the accumulation of nuclear wastes. That is not necessarily the case. A large global inventory of separated special nuclear material (mainly plutonium and highly enriched uranium) exists and will continue to grow, due to an imbalance of its production and utilization. There is already an accumulation of global spent fuel inventory in excess of 230,000MT as of 2000. A "business as usual" scenario results in:*

- *more than 250MT of separated plutonium (Pu) by the end of the decade,*
- *a large inventory of separated weapons-grade Pu from dismantled weapons, 100MT of which has been declared excess by the U.S.A. and Russia,*
- *the possible use of this weapons grade Pu in the civilian fuel cycle, increasing the burden for safe and secure management,*
- *large quantities of highly enriched uranium (HEU),*
- *more than 250 research reactors in over 60 countries using HEU as fuel,*
- *a global accumulation of approximately 900,000 MT of spent fuel by 2050, a capacity equal to more than a dozen Yucca Mountain sized repositories.*

*A return to substantial new nuclear power must satisfy a number of well described criteria; plants must be economical, safe, minimize waste production, be proliferation-resistant, and be acceptable to the public. Financing for these capital-intensive plants must be made available. Beyond these factors, it is timely as the 50th anniversary of the Atoms for Peace initiative approaches, to look at the features appropriate to a new nuclear regime. A combination of new technology; coordinated, international fuel cycle services; and a set of system-wide objectives could set the vision for a new nuclear regime which would simultaneously provide the option to meet future energy demands while reducing the national security and waste management challenges below where they are today.*

## 1. Introduction

Nuclear energy currently accounts for about 16% of the global electricity consumption. Despite its contributions and anticipated great potential, nuclear energy stands at a crossroad, facing significant challenges in terms of economic competitiveness, safety, non-proliferation and radioactive waste management. Of these four, the last two are fuel-cycle related and have become the most intractable techno-institutional challenges to the peaceful use of nuclear energy.

There is a false assumption that stopping nuclear power is the most effective way to minimize proliferation and stop the accumulation of radioactive wastes. The truth is that the global inventory of separated special nuclear material (SNM, mainly plutonium and highly enrich uranium) will continue to grow, due to an imbalance of its production and utilization. Also, there is already an accumulation of global spent fuel inventory in excess of 230,000 MT as of 2000. This inventory will continue to grow by continuously operating existing nuclear reactors. In a “business-as-usual” scenario:

- The global stock of separated plutonium (Pu) will continue to grow[1], as shown in Figure 1. On civil Pu alone, the total will be in excess of 250 MT by the end of this decade.
- There is a large inventory of separated weapons-

grade (WG) plutonium in nuclear weapons countries. Dismantling of nuclear weapons and the subsequent use of excess WG Pu in civilian fuel cycle will increase the burden for safe and secure management of separated Pu. The US and Russia have each declared 50 MT of WG Pu excess and signed a bilateral agreement to disposition 34 MT from each excess stock[2]. There is no plan for disposition of the remaining 16 MT of excess plutonium from each country.

- Highly enriched uranium (HEU), produced primarily to support nuclear weapons programs has been accumulated in a large global inventory of ~1900 MT (Table 1). The US and Russia declared a total of 674 MT excess. Of these, 500 MT of Russia HEU are being blended-down to low enriched uranium (LEU) for use as fuel in western reactors.

**Table 1. Global Inventory of Highly Enriched Uranium[3]**

| Country | Estimated HEU Inventory (MT) | Excess HEU (MT) | HEU Production End (year) |
|---|---|---|---|
| **United States** | 750 | 174 | 1988 |
| **Russian Federation** | 1050 | 500 | 1987 |
| **United Kingdom** | 21.9 | None | 1963 |
| **France** | 25 | None | 1996 |
| **China** | 20 | None | 1987 ?? |
| **India** | Very small | None | ongoing |
| **Pakistan** | 0.2 | None | ongoing |
| **Israel** | Unknown | None | ongoing |
| **Total** | ~1870 | 674 | |

- More than 250 research reactors (RRs) in over 60 countries once used or still use HEU as fuel. According to IAEA database[4], those current RRs with power rating > 5 MWt and fueled with HEU of 90% or more $^{235}U$ are listed in Table 2. These RRs face problems of reduced utilization and continued accumulation of spent fuel. Some spent fuels are barely irradiated and contain significant amount of HEU.

**Table 2. Country's Research Reactors, Types, Power Levels, and Enrichments (>90%)**

| Country | Reactor | Type | Power MW | Enrich-ment % |
|---|---|---|---|---|
| **Belgium** | BR-2 | $H_2O$ | 100 | 93 |
| **Canada** | MNR | $H_2O$ | 5 | 93 |
| **China** | HFETR | $H_2O$ | 125 | 90 |
| | MJTR | $H_2O$ | 5 | 90 |
| **France** | HFR | $D_2O$ | 58.3 | 93 |
| | ORPHEE | $H_2O$ | 14 | 93 |
| **Germany** | FRJ-2 | $H_2O$ | 23 | 93 |
| | BER-2 | $H_2O$ | 10 | 93 |
| **Greece** | GRR-1 | $H_2O$ | 5 | 93 |
| **Israel** | IRR-1 | $H_2O$ | 5 | 93 |
| **Japan** | KUR | $H_2O$ | 5 | 93 |
| **Kazakhstan** | EWG 1 | $H_2O$ | 60 | 90 |
| **Netherlands** | HFR | $H_2O$ | 45 | 93 |
| **Romania** | Triga-II | $H_2O$ | 14 | 93 |
| **Russia** | IR-8 | $H_2O$ | 8 | 90 |
| | BR-10 | FR* | 8 | 90 |
| | WWR-M | $H_2O$ | 18 | 90 |
| | IVV-2 | $H_2O$ | 15 | 90 |
| | MIR-M1 | $H_2O$ | 100 | 90 |
| | IRT-T | $H_2O$ | 6 | 90 |
| | SM-3 | $H_2O$ | 100 | 90 |
| | BOR-60 | FR | 60 | 90 |
| **South Africa** | SAFARI-1 | $H_2O$ | 20 | 93 |
| **US** | ATR | $H_2O$ | 250 | 93 |
| | MIT R-II | $H_2O$ | 4.9 | 93 |
| | NBSR | $D_2O$ | 20 | 93 |
| | HFIR | $H_2O$ | 85 | 93 |
| | U. M. | $H_2O$ | 10 | 93.15 |
| | Fast Burst | FR | 10 | 93 |

Note:
* FR – fast reactor

- Plutonium in spent fuel may become a proliferation risk when the spent nuclear fuel (SNF) eventually loses its self-protecting radiation (after ~300 years of decay). Currently, the amounts of SNF and its Pu contents are growing substantially in the US and around the world. Figure 2 shows the trends of total global inventories of Pu in SNF, including those in the US, RF, and the rest-of-world (ROW). It also shows that the global accumulated SNF could reach an inventory of ~900,000 MT, a capacity equivalent to 14 Yucca Mountain (YM, with a statutory capacity of 63,000 MT) at around 2050. The US spent fuel inventory will exceed the YM statutory capacity by early next decade.

- Public confidence on nuclear energy was tarnished since TMI and Chernobyl. Public debate and skepticism over the long-term disposal of radioactive wastes also undermine the credibility, if not the viability of nuclear power.

- In a de-regulated and privatization environment, the US nuclear industry faces steep competition for electricity generation from other fuel sources. This is happening when the US nuclear technological capability is in the midst of a steady decline. As the US nuclear industrial base vanishes and its infrastructure erodes, its global market share will eventually diminish.

For a return to substantial new nuclear power in the US and in the world, a "business-as-usual" approach cannot be afforded anymore. Instead, we must pursue a New Nuclear Regime in which nuclear power is economically competitive, safe, and acceptable to the public. And more importantly, the new regime must

- reduce the proliferation risk by drawing down and bringing inventories of weapons-usable materials under strict controls,
- minimize the environmental risk by reducing the spent fuel wastes and repository needs,
- build toward a common international framework to reduce the proliferation and environmental risks.

## 2. Reducing Proliferation Risk

Fissionable nuclear materials are used and simultaneously generated in nuclear reactors. Since the dawn of the nuclear era, there has been a concern regarding the theft, diversion and misuse of fissionable nuclear materials intended for peaceful purposes. To minimize the proliferation risk, inventories of weapons-usable materials must be drawn down and brought under strict controls.

Separated plutonium inventories can be reduced by transmutation in nuclear reactors. The US and Russia will each disposition 34 MT of excess WG plutonium in light water reactors (LWRs). At the end of the US-Russia Bilateral Agreement (2025), the remaining 16 MT of excess WG Pu from each country can be used to fuel fast reactors. These reactors can be operated with a breeding ratio (BR) of 1 to conserve plutonium as the reactor produces as much plutonium as it consumes. A fast reactor can also be operated with a BR of 0.65 to reduce the overall plutonium inventory. Figure 3 illustrates the trends of separated Pu stocks in Russia, the US and UK using Pu as fuel in fast reactors with different BRs.

HEU inventory can be reduced by blending it with depleted or natural uranium to produce LEU. The reduction rate will depend on the demand of the enrichment and natural uranium markets. To reduce the use of HEU in research reactors (RRs), the US has a program on Reduced Enrichment of Research and Test Reactor (RERTR), converting the RR core to use LEU as fuel, and taking back spent fuel from US-origin RRs. The RERTR program will end in May 2006.

Plutonium in spent nuclear fuel can be reduced by radioactive decay, which takes hundreds of thousands of years, or by reprocessing and recycling into nuclear reactors. If plutonium in existing and future spent fuel is recovered and re-used, it would be prudent to ensure that the recycling technologies are applied not only to reduce the proliferation risk, but also the environmental risk as well.

## 3. Reducing Environmental Risk

Currently, spent nuclear fuel (SNF) and/or high-level radioactive wastes (HLW) are accumulated on or off reactor sites pending on final disposal in geologic repositories. To minimize the environmental risk and repository need, the spent fuel waste volume has to be reduced. Here, we envision an advanced concept with fast reactors and innovative separation and fuel fabrication technologies to be employed in the New Nuclear Regime. The concept involves spent fuel reprocessing and separation of selected radionuclides.

In this concept, plutonium would be recovered, mixed with depleted or natural uranium and fabricated into fuel for fast reactors. Uranium, separated from SNF would either be recycled together with the separated plutonium in fast reactors, or be isotopically enriched to LEU and recycled to other U-fueled LWRs.

$^{90}$Sr and $^{137}$Cs would be separated and stowaway in a monitored surface facility until they decay away (in a time period approximately 10 times their respective half-lives). $^{135}$Cs could be isotopically separated, albeit the process is difficult because of the intense radiation of $^{137}$Cs, or it can stay with other Cs isotopes in the surface store for ~300 years and then be disposed of in a repository. Other long-lived radionuclides ($^{99}$Tc, $^{129}$I, and $^{237}$Np, etc.) would be separated and fabricated into target elements and transmuted in nuclear reactors.

The removal of the heat-generating isotopes (primarily $^{90}$Sr and $^{137}$Cs) could potentially reduce the acreage area of a spent-fuel repository by a factor of 8. Transmuting the fissionable nuclear materials (Pu, $^{235}$U, $^{237}$Np and other minor actinides) can reduce the potential for criticality in underground repositories. In addition, these fissionable materials can fuel fast reactors and generate electricity. For example, Pu in the spent fuel discharged from existing US reactors can be recovered and recycled in fast reactors which generate 43 GWe of electricity, as shown in dotted lines of Figure 2.

The concept requires cost-effective reprocessing technologies. At present, the PUREX reprocessing process is not economical in several countries (notably, the US). Other innovative and advanced separation technologies, such as dry or pyrochemical processes are needed to be developed and deployed to defray the high reprocessing costs and reduce the environmental burden of disposing radioactive wastes.

Ultimately, radioactive waste (HLW and/or SNF) will be disposed of in geologic repositories. Several countries have begun their national repository programs at specific or generic locations. Table 2 shows the countries' underground waste facilities.

**Table 2. Global Underground Waste Facilities**

| Country | Location | Rock Type | Waste Form | Site |
|---|---|---|---|---|
| Belgium | Mol | Clay | SNF/HLW | S* |
| Canada | Lac du Bonnet | Granite | SNF | G** |
| Finland | Olkiluoto | Granite | SNF | G/S |
| France | Tournemire | Shale | SNF/HLW | G |
| Germany | Konrad<br>Gorleben | Shale<br>Domal Salt | ILW/LLW<br>SNF/HLW | S<br>S |
| Japan | Tono | SandsMT | SNF/HLW | G |
| Sweden | ASPO | Granite | SNF | G |
| Switzer-land | Grimsel<br>Mont Terri | Granite<br>Shale | ILW<br>HLW | G<br>G |
| US | Carlsbad<br>Yucca Mountain | Bedded Salt<br>Tuffs | TRU<br>SNF/DHLW | S<br>S |

Notes:
* S – Specific site
** G – Generic site

Although repository technologies and approaches pursued by countries are site-specific, the challenge to repository development is institutional and political. To obtain public and stakeholders' acceptance and support for a repository site location,

- The program need must be convincingly established,
- Roles and responsibilities of stakeholders must be clear,
- Respect for societal consent must be apparent,
- Decision making process must be transparent and open,
- The program must be robust with possibility of alternating or reversing course.

## 4. Need for an international framework

Following the Atomic for Peace initiative by President Eisenhower in 1953, the International Atomic Energy Agency (IAEA) was established in 1957 to promote the peaceful use of nuclear energy and provide safeguards and inspections of nuclear facilities and materials. The Non-Proliferation Treaty (NPT) of 1968, signed now by more than 170 countries serves the purpose of limiting the number of weapons states to those already-declared before the initiation of NPT.

Since safeguards is needed for as long as the nuclear materials remain at the facility sites regardless whether the facilities are in operation or shutdown, there will be a continuous effort and traditional measures imposed on the owners of these facilities, resulting in a continuous financial and resource commitment. For example, Table 3 shows the number of person-days of inspection performed by IAEA annually for typical declared facilities[5].

**Table 3. Safeguards Inspection Effort, Traditional Measures on Declared Nuclear Facilities**

| Type of Facility | Person Days of Inspection per Year |
|---|---|
| Light Water Reactor, no MOX | 6 - 12 |
| CANDU Reactor | 45 |
| Light Water Reactor with MOX | 15 - 45 |
| Enrichment Plant | 70 - 150 |
| MOX Fuel Fabrication Facility | ~ 200 |
| Reprocessing Plant | > 750 |

For countries with small nuclear power programs and small amount of spent fuel and radioactive wastes, and those with dense population and small geographic areas, finding a suitable site for a repository may be difficult. These countries may also have limited potentials and resources to develop their own systems for managing their spent fuel and radioactive wastes. Furthermore, it may not be in the interest of the international community that spent-fuel repositories are spread out all over the world which may constitute a long-term proliferation risk.

Institutionally, an international framework of providing fuel-cycle services through a global network of fuel cycle facilities should be pursued. Such a network, if formed, could provide a cradle-to-grave, economically-competitive, safe, proliferation-resistant, and environmentally-friendly fuel cycle services to utilities and countries operating nuclear reactors for purpose of electricity generation. Utilities and countries acquired such services from the network will be free from the burden of nonproliferation and the need to deal with radioactive wastes.

Figure 4 show the concept of a global network of nuclear fuel cycle facilities[6]. Most of the fuel cycle facilities shown in Figure 4 are currently in operation (or under construction) in many countries. There are front-end fuel cycle facilities, including conversion, enrichment, and fabrication facilities for various fuel types, and back-end facilities, such as reprocessing and on-site spent fuel storage already available to serve the fuel cycle service needs. A few key facilities in the back-end fuel cycle, notably the regional spent fuel storage and waste repository are still absent in the global network.

The fuel cycle facilities in this global network are not necessarily owned by a country, nor need to be co-located in a "fuel-cycle center[7]". In fact, such a network could be formed merely by contractual agreements between two fuel cycle facilities or among a few parties. The aim is to ensure a stable and reliable supply of fresh nuclear fuel and to take the spent fuel back from reactor operators. Currently, reliable front-end fuel-cycle services are provided to reactor operators in a cost-competitive manner.

The importance of the global network of nuclear fuel cycle facilities is to relieve the burden of nonproliferation and wastes to countries/utilities operating nuclear reactors for electricity generation. If fresh nuclear fuel can reliably be supplied and the spent fuel removed, the country/utility may have less incentive to pursue its own fuel-cycle capabilities. This would be "win-win" for reactor operators and international safeguards because significant saving on inspection costs can be incurred as spent fuels are not in prolonged on-site storage. Furthermore, the inspection effort could be more focused on fuel-cycle facilities within the network. As many of these facilities are operated by and located in declared weapons states, safeguards inspection obligations are exempted or minimized.

The global network of nuclear fuel cycle facilities is by no mean a restriction to a country's own fuel cycle development. It is only an institutional alternative aiming at improving nonproliferation and radioactive waste management. Should a country decides to develop its own fuel cycle capability, it should prepare to deal with the nonproliferation and wastes issues in a manner conforming to international norms.

## 4. Conclusion

Despite its current contributions to energy supply, nuclear energy will not be able to fulfill its anticipated great potential unless the issues associated with nonproliferation and radioactive waste management are resolved. In our view, a "business-as-usual" approach toward nuclear energy can no longer be afforded. Instead, a "New Nuclear Regime" promoting the use of advanced technologies and a formation of an international framework should be pursued.

Advanced technologies should be employed to reduce the proliferation and environmental risks posed by the spread of separated nuclear materials and the accumulation of spent fuel and radioactive wastes. These technologies can be used to reduce the separated plutonium inventories and spent fuel waste volume, and hence the repositories needs. In addition, development of advanced technologies could help revitalize the US nuclear capability and infrastructure, and reassert the US global leadership and influence in the nuclear areas.

If a global network of nuclear fuel cycle facilities can be formed in the New Nuclear Regime, the burden of nonproliferation and wastes to countries/utilities operating nuclear reactors for electricity-generation can be lessened. The network can provide full-scope fuel cycle services which are economically competitive, meeting all applicable international safety standards, and complying with international safeguards and security requirement. It does not need to be within a national boundary, nor in a nuclear fuel cycle center.

References:


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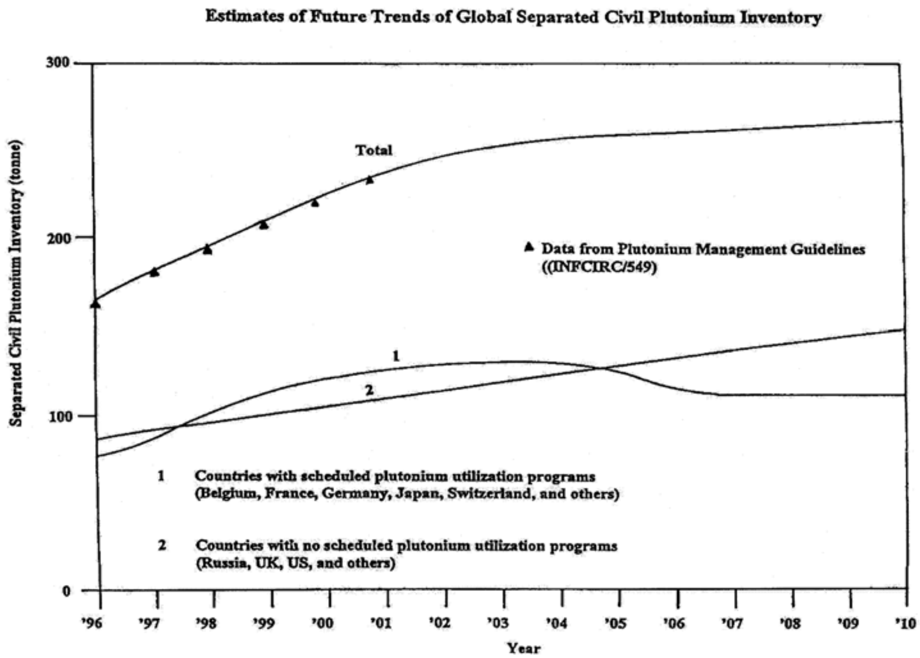


**Figure 1. Separated Civil Plutonium (Pu) Inventory**

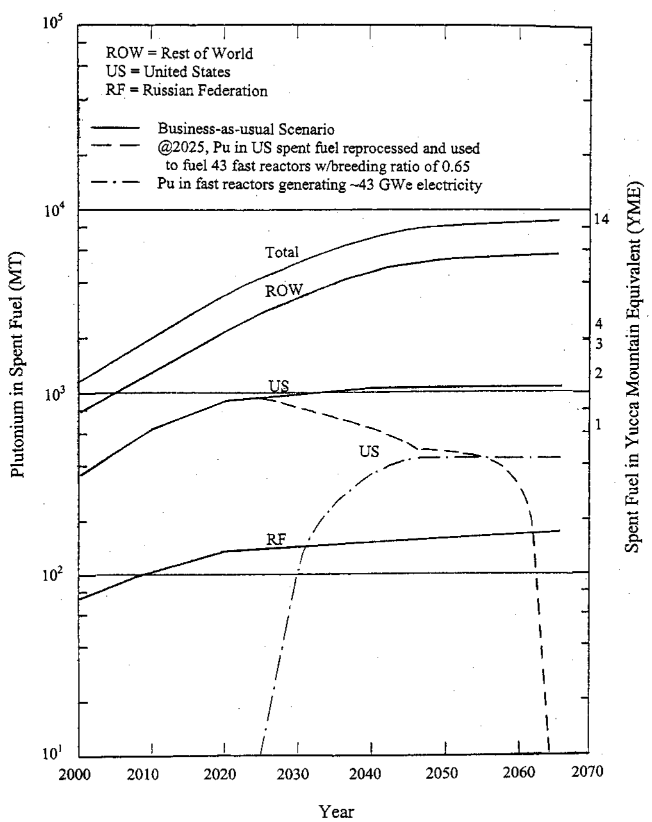


**Figure 2.** **Inventory of Spent Fuel in unit of Yucca Mountain Equivalent (YME) Capacity (63,000 MT/YME) and Projected Inventory of Plutonium in Spent Fuel**

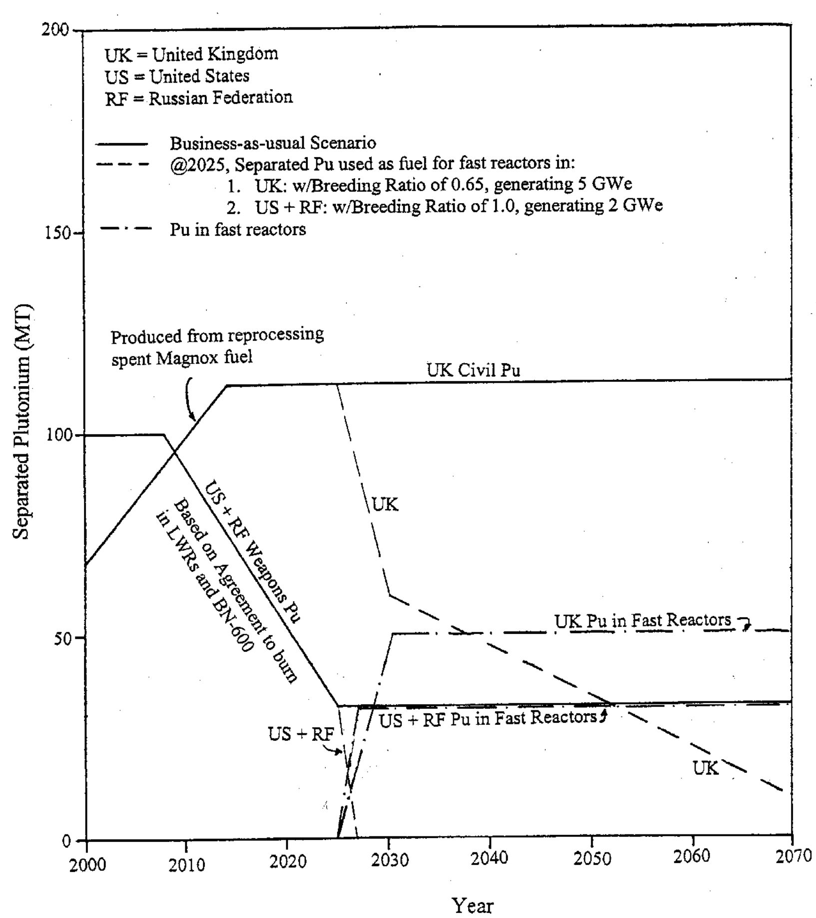


**Figure 3. Trends of Separated Plutonium stocks in RF, UK, and the US**

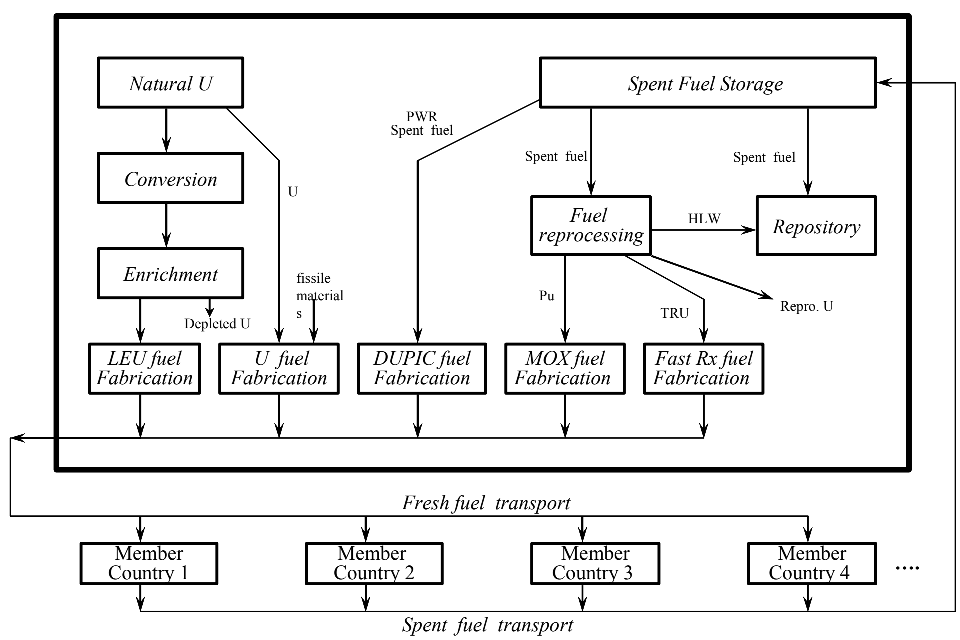


**Figure 4. A Global Network of Nuclear Fuel Cycle Facilities**